FINAL REPORT

Assessing 30 years of changes in vegetation and fuels following wildfire in jack pine forests of northern Lower Michigan

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Acknowledgements

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Abstract

The importance of vegetation and fuels in coniferous forests of North America have long been recognized from an ecological and fire management perspective. With the onset of a warming climate and the potential for increased periods of drought in the Lake States, ecosystems dominated by jack pine are likely to experience more frequent and severe wildfires, with potential impacts on a multitude of ecosystem services. Quantifying the dynamics of vegetation structure and fuel loadings in these systems in ways that will inform predictions of successional pathways and/or fire behavior is critical, but the amount of empirical data available that allow for accurate prediction of crown fire behavior and spread is low in part because fuel loadings and the changes they undergo during succession are not adequately described. Quantitative data describing how vegetation and fuels change over time to influence flammability in this system could therefore be critical for its translation into decision-making aids for managers as they begin to re-instate the practice of prescribed burning. I conducted field work in 2017 using permanent plots sampled in northern Lower Michigan in 1986 and 1996 and used these data to parameterize the Lake State Variant of the Forest Vegetation Simulator (FVS) to examine changes in vegetation and fuels over a 37-year period of succession. Field data suggested that ecological species groups developed specifically for these ecosystems were less able to differentiate ecosystems across the landscape as succession proceeded, likely because their coverages decreased dramatically following canopy closure. Successional changes in fuels featured a peak of canopy coverage and ladder fuels in mid-succession, suggesting that crown fire potential is reduced in older stands. Using field data as a reference, FVS poorly modeled fuels in this system, underestimating litter and duff while overestimating fine woody fuels. FVS did not represent stand dynamics of these systems well. Simulations with Behave Plus suggested that crown fires were most likely to occur in younger stands and decreased in likelihood in older stands, which was consistent with field data. These results reiterate the need for decision-making by fire managers to occur in a dynamic manner, without assumptions that current conditions will be present after even a few years of succession or stand development.

Objectives

The objectives of this study were designed to apply to Task Statement #7 of FA-FON0015-0001, as an examination of how successional patterns of vegetation and fuels vary temporally and spatially following fire. Specifically, the overall objective of this project was to understand how stand structure, the fuels complex, and plant community composition change with long-term succession following stand-replacing wildfires in jack pine-dominated ecosystems of northern Lower Michigan. I hypothesized that vegetation structure and fuel conditions will vary both with time since fire and spatially within a previously burned area, with the idea that the integration of these variations into land management strategies will contribute to sound decision-making in a fire-prone landscape.

I addressed the following three specific questions with this project:

1) *How does plant community composition change with succession, and how variable are these successional pathways across the landscape?*
   Based on previous sampling and my experience in the field, I hypothesized that plant community composition at the forest floor will change considerably based on the availability of light following canopy closure, and biodiversity will decrease with time. I also expected that composition of the overstory and understory will increase in deciduous species as succession proceeds, and that composition of all layers of these stands will vary across the landscape based on initial differences in stand density.
2) *How do vegetation structure and fuels change with succession, and how variable are these changes across a large fire-prone landscape?*
   My working hypothesis, based on field observations and previous data, was that important stand structural changes will occur such as canopy closure, the interlocking of dead branches, and the development of ladder fuels. I also expected that FEE_FVS predictions will compare favorably with empirical data over the 30-year sampling period that our plots represent.
3) *Do changes in vegetation and fuels have the potential to alter fire behavior and spread across the landscape?* I hypothesized that the successional changes over the 30 years represented by plot sampling will increase the likelihood of crown fire initiation and spread in this system.

Background

The importance of vegetation and fuels in coniferous forests of North America have long been recognized from an ecological and fire management perspective. In the northern Lake States region, dry, sandy glacial outwash plains support ecosystems dominated by variably dense, high-fuel jack pine (*Pinus banksiana* Lamb.) forests (Whitney 1986). Accordingly, the natural disturbance regime in jack pine-dominated ecosystems of this region is characterized by large-scale, stand-replacing crown fires (Heinselman 1973). This disturbance regime is perpetuated by dense post-fire regeneration via serotinous cones leading to dense stand conditions whose flammability is thought to increase with time (Van Wagner 1983, Bond and Midgely 1995; Figure 1). Fire suppression is the common management type in this system due to a fine-grained mosaic of public and private land ownership, and prescribed burning is generally uncommon because of heavy fuel loadings. With the onset of a warming climate and the potential for increased periods of drought in this region, these ecosystems are likely to experience more frequent and severe wildfires, with potential impacts on a multitude of ecosystem services. As jack pine-dominated ecosystems are a representative and dominant ecosystem type on the regional landscape of the northern Lake States and elsewhere, quantifying the dynamics of vegetation structure and fuel loadings in these systems in ways that will inform predictions of successional pathways and/or fire behavior is critical.

Figure 1. Characteristic changes in jack pine forest structure in northern Lower Michigan from 5 years post-fire (top), 16 years post-fire (center), and 37 years post-fire (bottom).

Fuels management and reduction has been a major consideration across the country for the last two decades, though targeted systems are most typically those characterized by surface fires or mixed-severity regimes (Brown 1995). Management in crown fire systems, where fires are typically larger and more intense and where fire suppression is less effective, often relies on the creation of fuel breaks and defensible space. The amount of empirical data available that allow for accurate prediction of crown fire behavior and spread, including that for jack pine- dominated ecosystems in the northern Lake States, is low in part because fuel loadings and the changes they undergo during succession are not adequately described.

Wildfires historically maintained jack pine-dominated forests across xeric glacial outwash landforms in northern Lower Michigan, with fire return interval estimates ranging between 35 (Simard and Blank 1983) and 59 years (Cleland et al. 2004). High stand densities lead to crown fire initiation in these stands (Bond and Midgely 1995), but flammability in jack pine is also promoted by low foliage moisture, high levels of combustible compounds (Whitney 1986, Fonda 2001), and high fuel continuity resulting from between-tree interlocking of retained dead branches (Johnson 1994, Stocks 1989). The Mack Lake Fire of 1980 on the Huron-Manistee National Forest of northern Lower Michigan is one of the largest wildfires on record for the eastern United States, burning 23,830 acres (9,532 ha) in < 14 hours. Four additional major wildfire events have occurred within the 1980 burn perimeter since 1999, reflecting both the potential for crown fire that remains on the current landscape and its increased flammability with increasing age. Large crown fires such as that at Mack Lake are usually driven by extreme fire weather conditions (Simard et al. 1983) following ignition and are difficult to predict, burning across complex and variable fuel conditions and stand structures. However, smaller, more frequent crown fires exhibit behavior more subject to variations in fuels and stand structures. Notably, the first prescribed crown fire in live jack pine – which was used to burn 50 acres directly adjacent to the Mack Lake subdivision – was performed by U.S. Forest Service (USFS) officials in June 2014, demonstrating the desire for local managers to reinstate prescribed burning used to reduce fuel loadings (S. Goldman, pers. comm.). Quantitative data describing how vegetation and fuels change over time to influence flammability in this system could therefore be critical for its translation into decision-making aids for managers as they begin to re-instate the practice of prescribed burning. Moreover, results from such research will be useful for shaping the degree and number of fuel breaks and other hazardous fuels reduction projects in the private/public land interface.

Materials and Methods

Overview

This project re-measured vegetation structure, fuels development, and plant community composition in jack pine forests of northern Lower Michigan and integrated these data into a modeling framework to predict potential changes in crown fire behavior in jack pine over time. Permanent plots first established in 1986, re-sampled in 1996, and re-located in 2007 were re-measured to represent a third point along a 37-year successional sequence. Results were then compared to vegetation and fuels development predictions in the Base Model and Fire and Fuels Extension of the Forest Vegetation Simulator (FEE-FVS). Field data was then utilized within FVS to predict potential fire behavior at each site under similar abiotic conditions.

Study site

This project was conducted on a landscape dominated by jack pine in the area burned by the Mack Lake Fire of 1980, located about 10 km south of Mio, Michigan on the Huron-Manistee National Forest. The study area is located within a large physiographic basin dominated by xeric, excessively drained sand soils on outwash plains and ice contact terrain (Walker et al. 2003). Overstory jack pine dominated about 42% of the area burned in 1980, with stand densities ranging from 250 to 12,500 stems/ha; minor stand types included scattered red pine (*P. resinosa* Sol. ex Aiton) plantations and mixed stands of pine and northern pin oak (*Q. ellipsoidalis* E.J. Hill; Simard et al. 1983). Current vegetation includes a dense, patchy mosaic of jack pine and jack pine mixed with northern pin oak (Walker et al. 2003). The pre-settlement fire interval for large fires (> 4,000 ha) in the area was estimated to be 35 years by Simard and Blank (1982); this estimate was increased to 59 years for jack pine in the larger region of northern Lower Michigan (Cleland et al. 2004). Four wildfires, heavily suppressed, have occurred within the area burned in 1980, including fires in 1999 (340 ha), 2000 (2014 ha), 2006 (2345 ha), and 2012 (323 ha). The area is currently managed for the federally endangered

Kirtland's warbler, mainly by establishing dense jack pine plantations in areas where stocking density was low following wildfire. Extensive fuel breaks have been established near a small subdivision in the center of the Mack Lake basin that was heavily impacted by the 1980 wildfire. A small prescribed crown fire in standing timber was successfully completed in the area in Spring 2014.

Field sampling design

Methodology used for original sampling and original data have been published in Zou et al. (1992), Kashian et al. (2003a, b), and Walker et al. (2003). A total of 41 plots were re-measured for this project in 2017-18, with 27 plots established in 1986 and sampled in 1986 and 1996; and 14 established and sampled in 1996 only. This design provided sample periods at 6, 16, and 37 years for those plots established in 1986 (Zou et al. 1992), and at 16 and 37 years for those established in 1996 (Walker et al. 2003). Plot sampling was dictated by the number of available plots left undisturbed in the field since 1996; several plots re-located in 2007 had since been clear cut or burned (Table 1). Plots were 10 x 20 m in size and were divided into eight equal 5 x 5 m subplots.

Changes in community composition

Vegetation data sampled at the plots in both 1986 and 1996 included an entire inventory of all species < 1.5 cm DBH, including tree seedlings and saplings, shrubs, forbs, graminoids, ferns, mosses, and lichens; these data were re-sampled in 2017-18 as part of this project for two

Table 1. Distribution of permanent sampling plots by year established, and number relocated in 2017-2018.

<table>
<tr><th>Year Established</th><th colspan="2">1986</th><th colspan="2">1996</th><th>Total</th></tr>
<tr><td>Original Total</td><td colspan="2">47</td><td colspan="2">19</td><td>66</td></tr>
<tr><td rowspan="4">Not Relocated in 2017</td><td>Undisturbed but rebar not found</td><td>12</td><td>Undisturbed but rebar not found</td><td>0</td><td rowspan="4">25</td></tr>
<tr><td>Planted over for KW habitat</td><td>3</td><td>Planted over for KW habitat</td><td>0</td></tr>
<tr><td>Clear Cut between 1997-2013</td><td>4</td><td>Clear Cut between 1997-2013</td><td>4</td></tr>
<tr><td>Clear Cut between 2013-2017</td><td>1</td><td>Clear Cut between 2013-2017</td><td>1</td></tr>
<tr><td>Relocated in 2017</td><td colspan="2">27</td><td colspan="2">14</td><td>41</td></tr>
</table>

purposes. First, data collected in 1996 were originally used to develop groups of ground flora species –ecological species groups - that may be used by local managers to characterize and distinguish between landform-scale ecosystems dominated by jack pine in northern Lower Michigan based on their indicator value of site quality (Table 2; Kashian et al. 2003b). A major

Table 2. Ecological species groups developed for jack pine-dominated ecosystems of northern Lower Michigan (Kashian et al. 2003a).

Ecological Species Groups	Soil Moisture*					Soil Fertility*				
	very dry	**dry**	**slightly moist**	**mod. moist**	**very moist**	**very infertile**	**infertile**	**slightly infertile**	**mod. fertile**	**very fertile**
***Danthonia* group**										
Danthonia spicata (L.) R&S, *Andropogon gerardii* Vitman., *Schizachyrium scoparium (* Michx.) Nash, *Arctosaphylos uva-ursi* (L.) Sprengel, *Hieracium floribundum* Wimmer&Grab., *Hieracium venosum* (L.)										
***Solidago* group**										
Solidago simplex Kunth, *Anenome quinquefolia* L., *Viola pedata* L.										
***Vaccinium* group**										
Vaccinium angustifolium Aiton, *Carex pensylvanica* Lamb., *Comptonia peregrina* (L.) Coulter, *Melanpyrum lineare* Desr., *Prunus pumila* L.										
***Maianthemum* group**										
Maianthemum canadense Desf., *Amelanchier spicata* (Lamb.) K. Koch, *Oryzopsis asperifolia* Michx.										
***Gaultheria* group**										
Gaultheria procumbens L., *Amelanchier sanguinea* (Pursh) DC, *Epigaea repens* L, *Solidago hispida* Willd.										
***Crataegus* group**										
Crataegus spp. L., *Convolvulus arvensis* L., *Rosa blanda* Aiton										
***Fragaria* group**										
Fragaria virgininiana Miller, *Prunus serotina* Ehrh., *Rubus flagellaris* Willd., *Salix humilus* Marsh., *Schizachne purpurascens* (Torr.) Swallen.										
***Rubus* group**										
Rubus hispidus L., *Spiraea latifolia* (Aiton) Borkh.										
Developed for KW Breeding Habitat by Kashian et al. (2003)	**very dry**	**dry**	**slightly moist**	**mod. moist**	**very moist**	**very infertile**	**infertile**	**slightly infertile**	**mod. fertile**	**very fertile**
	Soil Moisture*					**Soil Fertility***				

hypothesis of this work was that the groups should be effective at distinguishing among ecosystems even as stand structure changed with age because each group contained early- as well as late-successional species. Re-measured ground flora data was used to test the validity of the ecological species groups 20 years after their development. Second, a study by Abrams et al. (1985) conducted across northern Lower Michigan suggested that the individualistic nature of each site was more important than stand age following disturbance in jack pine-dominated ecosystems. These conclusions are important for managers interested in conserving some level of biodiversity across the landscape and were tested using the 37 years of ground cover data presented in this study.

Shannon's Diversity Index and Evenness were used to analyze changes in plant diversity. Sorenson's Coefficient of Community Similarity was used to examine intra-site changes in community composition for twenty-seven of the re-sampled sites (Abrams et al. 1985). The coverage of ecological species groups in 2017-2018 was compared to those collected in 1986-87 (Zou et al. 1992) and 1995-96 (Walker et al. 2003). The total median percent cover of the ecological species groups developed by Kashian et al. (2003a) for jack pine-dominated ecosystems in northern Lower Michigan were compared across sampling years using the non-parametric Friedman Test using a Wilcoxon Signed-Rank test as a post-hoc test and a Bonferroni adjustment for multiple comparisons. Differences in the distribution of ecological species groups among the regional landform groups developed by Kashian et al. (2003a; Table 3) for a given year were assessed using the Kruskal-Wallis H test separately for each sampling year, and an adjusted significance level for multiple pairwise comparisons done post-hoc. To analyze whether the indicator value of the ecological species groups was robust across the successional sequence, a canonical variates analysis (CVA) was performed to assess the ability of the ecological species groups to differentiate the landform-level ecosystems at each time period.

Table 3. Landform-level ecosystems dominated by jack pine identified across northern Lower Michigan by Kashian et al. (2003a) and present at the Mack Lake Burn (Walker et al. 2003).

Landform Group	Description
Glacial outwash channels	Low-lying, extremely flat topography; coarse and medium-coarse sand with pebbles and cobbles; banding uncommon or absent; excessively drained; cold and very infertile.
Unbanded outwash plains	Flat to moderately sloping or pitted; medium-coarse sand and gravel to medium-fine sand; banding uncommon or absent; excessively drained; infertile.
Banded outwash plains	Flat to moderately sloping or pitted; medium to very fine sand; banding common to frequent; somewhat excessively drained; moderately infertile.
Water table-influenced outwash plains	Flat topography; medium-fine to fine sand; banding occasional to absent; somewhat poorly drained; water table within 2 meters of surface; infertile.
Ice-contact terrain and associated outwash plains	Flat to slightly or steeply sloping topography; medium sand to sandy loam; banding common to absent; excessively to well drained; infertile to moderately infertile.

Changes in vegetation structure and fuels

Plot level changes in fuels were also assessed by re-measuring vegetation data originally sampled in 1986 and/or 1996. Fuel loadings were sampled using FIREMON sampling methods (Lutes et al. 2006) to measure the amount of dead and down woody debris, duff and litter, and vegetation in a plot. Four transects were established at each plot, with the northeast corner marking their origin, each running in a cardinal direction (Figure 2). Dead and down woody debris (DWD) were re-sampled using the planar intercept method (Brown 1974) and identified as either fine woody debris (FWD) < 8 cm in diameter including 1-hour (< 0.6 cm), 10-hour (0.6 – 2.5 cm) and 100-hour fuels (2.5 – 8.0 cm), and coarse woody debris (CWD) > 8 cm in diameter and including 1,000-hour fuels. The number of FWD fuels in each class were tallied in the following manner: 1-hr and 10-hr fuels were counted between the 5 and 7 m marks along each transect, and 100-hr fuels were counted between the 5 and 10 m marks. The diameter of each piece of CWD was tallied and measured for biomass estimations and classified by decay class (Seedre et al. 2013) between the 5 and 25 m marks. Additionally, at the 10 and 20 m marks of each transect, a two-meter sampling radius was established for measuring duff and litter thickness and groundcover height and composition. The cover and height of vegetation was estimated for each of the following categories: live tree/shrubs, dead tree/shrubs, live herbs, and dead herbs. The diameter at breast height, tree height, and species were also recorded for the three dominant trees at the 10 and 20 m marks (Figure 2).

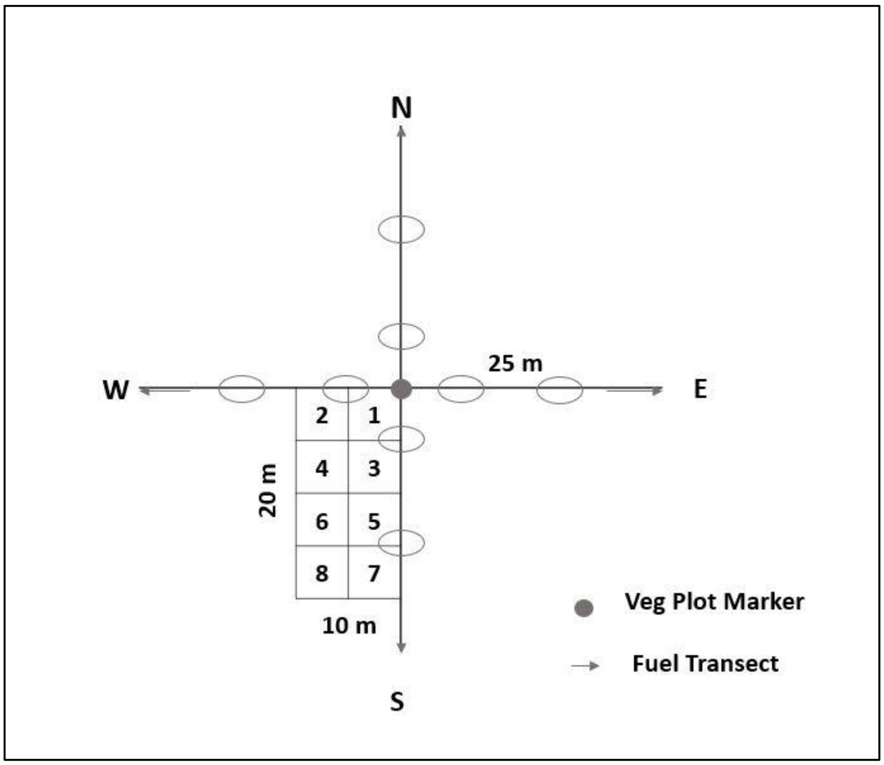


Figure 2. Sampling design for vegetation and fuel loads. The closed circle marks the northeast corner of the 200 m^2 vegetation plot and 5m x 5m subplots. Four transects extend outward in the cardinal directions for 25 m each. The open circles mark the 10 and 20 marks on a transect.

To assess changes in fuels and vegetation structure over time, all stand and fuel characteristics of the 27 plots available in all sampling periods were evaluated across the three sampling periods with the non-parametric methods described above. Stand variables were evaluated for distinctness across the landforms identified by Walker et al. (2003) using a Kruskal-Wallis H test and multiple pairwise comparisons. Biomass was estimated for duff and litter by multiplying thickness (cm) by a combined bulk density value of 5.4 lbs/ft3 (0.09 Mg/m3) reported by Simard et al. (1983) for Mack Lake soils. For CWD and FWD, biomass was calculated using equations developed by Brown (1974).

Effects of succession on fire behavior and spread
Vegetation data from all three sample periods was used to parameterize the Lake States variant of FEE_FVS to compare field data to successional changes predicted by the model. I used FVS to predict vegetation and fuels succession that was then compared to empirical field data. I used field data collected in 1986 and 1996 to initiate stand and tree growth simulations in FVS (Wykoff et al. 1982, Dixon 2002) using the Lakes States variant (Dixon et al. 2008). I simulated fire potential and fuels parameters using the Fire and Fuels Extension (Rebain et al. 2010). Input data from field measurements included tree parameters (height, diameter, crown height, crown ratio, age) and stand parameters (fuels data, location, aspect, slope, elevation, site index). I simulated stand dynamics with FVS using the Suppose interface and generated output using the Database Extension (Crookston et al. 2003). Simulations were run using 5-year increments and I compared outputs to the corresponding field data collected at the 3 points in time. I analyzed the simulations to test for differences in fuels and vegetation structure over time.

To test differences in amount of fuels between field-measured values and FVS-predicted values I used Kruskal-Wallis tests with Dunn-Bonferroni post-hoc pairwise comparisons, as normality could not be confirmed in all cases (IBM 2019). To test whether FVS accurately predicts stem density, I compared mean stem density between field measurements and FVS-generated stands based on both 1986 and 1996 data. I used 2-factor repeated-measures ANOVA with a Greenhouse-Geisser correction for violations of sphericity (IBM 2019). I used time (year of sample) and measurement method (field, FVS1986, FVS1996) as factors.

To generate potential fire behavior reports I used stand canopy parameters from FVS runs input into Behave Plus 5.0.5 (Heinsch and Andrews 2010) combined with fire weather scenarios for moderate and severe fire weather taken from local measurements (personal communication B. Stearns, USFS). I ran the model using the timber grass and understory fuel model (Anderson 1982) with severe and moderate weather measurements and FVS-generated stand canopy parameters to compare fire potential between years. I analyzed data with 2-factor repeated measures ANOVA with a Greenhouse-Geisser correction for violations of sphericity (IBM 2019).

Results and Discussion

Successional changes in stand structure and community composition
Jack pine was the dominant species throughout stand development, though there was a marked and expected decrease in density across the burned area that occurred with stand development. Total jack pine density was highest on average in 1986 and concentrated as seedlings, shifting to the understory in 1996 and decreasing in overall density. By 2017, 37 years after the fire, overall jack pine stem density was lowest as overstory trees began to senesce (Figure 3). Most stem loss occurred between 1996 and 2017, probably due to self-thinning (Peet and Christensen 1980, Westoby 1984). Dead overstory jack pine trees were present in densities at least 10% of those of live trees in 2017-18. Percent canopy coverage was lower in 1986 (18%) than 1996 (58%), and 2017 (38%) (Figure 4). Understory jack pine was the densest in 1996 compared to 1986 and 2017 (Table 4). Depending on site quality, mortality for jack pine forests may peak as late as 60 years post-fire (Rudolph and Laidly 1990, Kenkel et al. 1997), yet senescence has already begun after 37 years at Mack Lake, probably because of the more temperate climate in northern Lower Michigan supporting faster, shorter-lived trees compared to the boreal

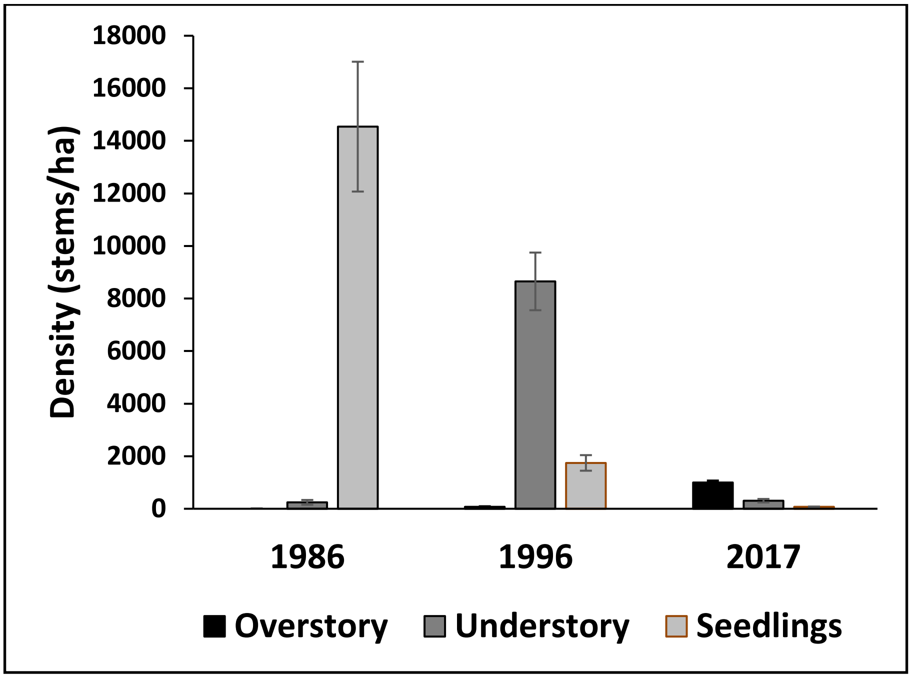


Figure 3. Changes in stem density of jack pine after the 1980 Mack Lake Burn for the 27 sites measured in 1986, 1996, and 2017.

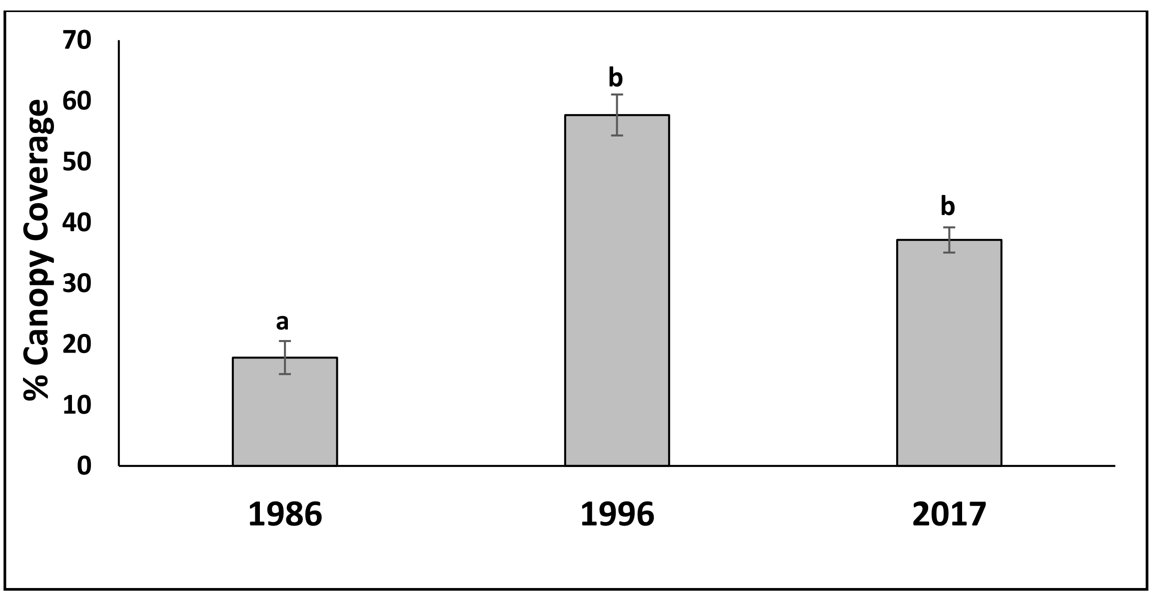


Figure 4. Changes in canopy coverage over time for the 27 sites measured in 1986, 1996, and 2017. Percent canopy coverage was significantly lower in 1986 than both 1996 ($p < 0.001$) and 2017 ($p = 0.001$); canopy coverage in 1996 and 2017 did not differ significantly.

Table 4. Comparison of woody vegetation over time, averaged over the 27 sites measured in 1986, 1996, and 2017. Values are means with one standard error in parentheses. *Indicates significance at $\alpha = 0.05$; pairs sharing a letter are not significantly different.

	1986	**1996**	**2017**
% Coverage of canopy*	18 (3)	58 (4)	38 (2)
Density (# stems/ha) of overstory *Pinus banksiana***	0^{a} (0)	74^{a} (22)	998^{b} (76)
Density of overstory *Q. ellipsoidales***	0^{a} (0)	9^{a} (5)	98^{a} (37)
Density of overstory *Acer rubrum*	0 (0)	0 (0)	20 (14)
Density of overstory *Populus grandidentata*	0 (0)	7 (7)	22 (22)
Density of understory *Populus tremuloides*	126 (126)	198 (191)	11 (11)
Density of total standing dead trees	0 (0)	2 (2)	228 (32)
Density of understory *P. banksiana***	233^{a} (91)	8652^{b} (1097)	307^{a} (67)
Density of understory *Q. ellipsoidales***	122^{a} (56)	361^{b} (106)	111^{ab} (37)
Density of understory *Acer rubrum*	15 (12)	85 (65)	80 (71)
Density of understory *Populus grandidentata*	13 (13)	13 (13)	6 (6)
Density of understory *Populus tremuloides*	126 (126)	198 (191)	11 (11)
% Coverage *Pinus banksiana* seedlings**	12.98^{a} (2.76)	1.65^{b} (0.89)	0.02^{c} (0.01)
% Coverage *Quercus ellipsoidales* seedlings**	3.92^{a} (1.10)	1.56^{ab} (0.48)	0.68^{b} (0.18)
% Coverage *Acer rubrum* seedlings**	0.00^{a} (0.00)	0.92^{a} (0.89)	0.09^{b} (0.06)

ecosystems most commonly reported in the literature (Rudolph and Laidly 1990).

Few jack pine seedlings were observed in 2017 (Table 4). Understory northern pin oak increased from 1986 to 1996, but then decreased in 2017 (Table 4). Oak seedlings were greater in 2017 than jack pine and all other tree seedling species combined (Table 4). The low number of jack pine seedlings present in 2017 suggests that it is unlikely that jack pine will replace itself on this landscape in the absence of fire; seed sources from non-serotinous cones will be reduced, and seedlings will struggle to establish without bare mineral soil or adequate light (Rudolph and Laidly 1990). In the absence of fire, many stands will begin to succeed to northern pin oak (except for the coldest sites; Kashian et al. 2003b, Walker et al. 2003) or perhaps red maple on the more mesic sites at Mack Lake.

There was a decline in species richness, total coverage, evenness, and Shannon's diversity of the sample plots over the 37-year sample period. Six years after the burn (1986), plots had higher groundcover diversity (H = 1.18) than in 1996 (H = 1.12) and in 2017 (H = 0.97). By 2017, species richness was lower (23 species) than in 1986 (28 species) and in 1996 (27 species); richness in 1986 and 1996 did not differ. Similarly, evenness of coverage was lower in 1986 (0.07) compared to 1996 (0.05) and 2017 (0.04). Total coverage of ground species decreased from 1986 (> 100%) to 2017 (61%) but did not change substantially from 1986 to 1996 or from 1996 to 2017. Sorenson's Coefficient of Community Similarity was between 0.5 and 0.7 for all three sampling years. The groundcover communities were, on average, most similar between 1986 and 1996 (CC = 0.65), and least similar between 1986 and 2017 (CC = 0.53) and 1996 and 2017 (CC = 0.60).

Successional changes in ecological species groups
All but one species (*Anemone quinquefolia* L. of the *Solidago* group) found in the ecological species groups created by Kashian et al. (2003a) were observed at Mack Lake in at least one of 1986, 1996, or 2017, but the coverage of the species groups changed across the three sample periods. Five of the eight species groups showed significant differences in their distribution of cover over time, pooled across landforms (Table 5). The *Danthonia* and *Vaccinium* groups showed significant decreases in mean cover between each successive sampling period. The *Danthonia* group was significantly lower in 2017 than both 1986 and 1996. The Vaccinium group decreased from 1986 to 1996 and again from 1996 to 2017. Significant declines in cover across time were also seen for the *Solidago*, *Crataegus*, and *Fragaria* groups, although no pairwise comparisons were significant. The *Gaultheria*, *Maianthemum* and *Rubus* groups did not change across the three sample periods (Table 5).

Only some of the ecological species groups maintained their indicator value over the course of succession, probably due to a reduction in the abundance of the groups over time. An important result of stand development is canopy closure, which will impact ground cover species composition (Ahlgren 1960, Abrams and Dickman 1982). Canopy cover at Mack Lake increased until least 1996 and decreased by 2017, which likely explains the decrease in species diversity, richness, and overall decrease observed for groundcover coverage from 1996 to 2017. Many species that were omnipresent between 1987 and 2017 were woody species that re-sprout vegetatively following fire and are tolerant of moderate shade (e.g., *Vaccinium angustifolium*, *Comptonia peregrina*, *Prunus pumila*, *Arctostaphylos uva-ursi*; Abrams and Dickman 1982, Crane 1991, Tirmenstein 1991, Snyder 1993). Where such species have indicator value across varying sites, they would appear to be particularly valuable for inclusion in ecological species groups as they would make the groups robust to changes in stand conditions and canopy cover over time. As the coverage of the species groups decreases with stand age, it is likely that the indicator value of the groups also decreases.

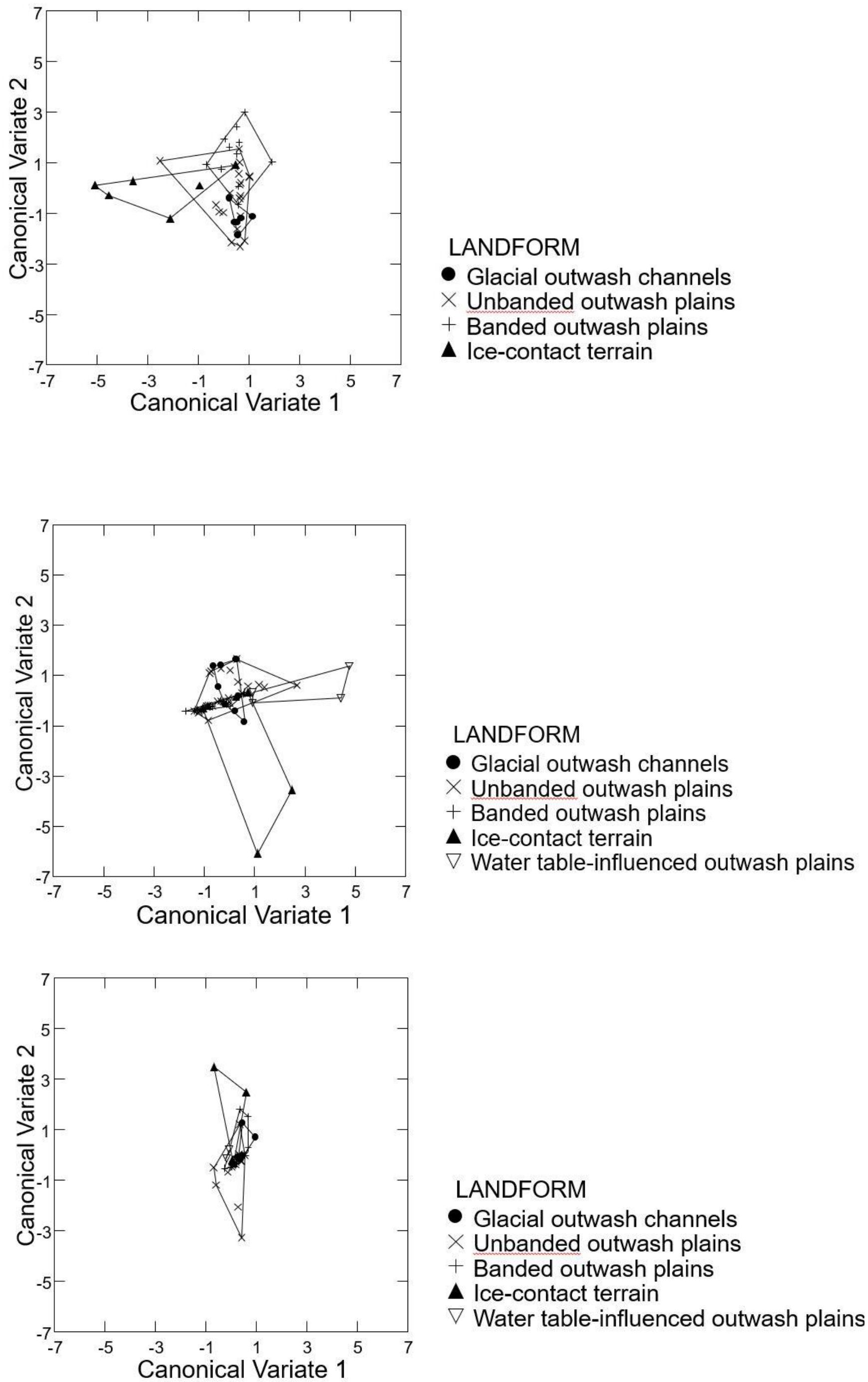
Table 5. Mean percent cover of the ecological species groups created by Kashian et al. (2003a) for jack pine-dominated systems in northern Lower Michigan. Values presented are for 27 plots measured in 1986, 1996, and 2017. One standard error is shown in parenthesis. *Indicates significance at α = 0.05; pairs sharing a letter are not significantly different.

Ecological Species Group	**1986**	**1996**	**2017**
*Danthonia**	3.41%[a] (1.17%)	1.16%[a] (0.28%)	0.13%[b] (0.03%)
*Solidago**	0.37%[a] (0.23%)	0.004%[a] (0.003%)	0.002%[a] (0.002%)
*Vaccinium**	53.84%[a] (6.04%)	28.83%[b] (5.12%)	14.05%[c] (3.44%)
Gaultheria	0.7% (0.24%)	0.90% (0.48%)	0.26% (0.07%)
Maianthemum	1.96% (0.76%)	3.29% (3.03%)	1.08% (0.63)
*Crataegus**	0.22% (0.09%)	0.13% (0.07%)	0.03% (0.01%)
*Fragaria**	2.19% (0.62%)	2.13% (0.98%)	0.69% (0.23%)
Rubus	0.03% (0.03%)	0.01% (0.01%)	0.004% (0.003%)

Canonical variates analysis showed that using the ecological species groups to differentiate the landform-level ecosystems at Mack Lake was only moderately successful at best, and the success of doing so varied over time. In 1986, the CVA classified the landforms correctly 63% of the time, which was the highest classification rate of the three sampling periods. The most common misclassification was among banded and unbanded outwash plains. The landforms showed good separation in ordinate space (Figure 5a), with the majority of the overlap occurring between the glacial outwash channels and the unbanded outwash plains, with the ice-contact terrain appearing the most distinct. In 1996, the CVA classified the landforms correctly 41% of the time. Most of the landforms displayed considerable overlap in ordinate space, except for the ice-contact terrain and water table-influenced outwash plains (Figure 5b). In 2017, the CVA classified the landforms correctly 48% of the time, with most overlap occurring between banded outwash plains and glacial outwash channels in ordinate space (Figure 5c). Future research should analyze how well the broad species groups distinguish landforms of individual sites across northern Lower Michigan, and whether local rather than broad ecological species groups (Walker et al. 2003) would discriminate plots better along local landforms.

Successional changes in fuels

The overall distribution of many fuel characteristics, including duff thickness, the biomass of coarse woody debris, the heights and coverage of live woody and herbaceous ground-level plants, the height of dead woody plants, and the percent coverage of moss, changed significantly over the three sample periods (Table 6). The most important changes in fuel loadings occurred in coarse woody debris (1000-hr fuels), which was initially high after the fire (1986), decreased in mid-succession (1996), then increased again as the stands matured (2017) to volumes still below initial post-fire quantities, similar to other studies of fire-generated jack pine (Spaulding and Rothstein 2009) and other forest types regenerated by fire (Kashian et al. 2013). Other components of the fuel complex changed much less over time, including fine woody debris (1-hr, 10-hr, and 100-hr fuels), which is also consistent with other researchers (Allard and Park 2013).



Figures 5a-c. Ordination of first two canonical discriminant functions of the ecological species data set for 1986 (top; n = 43), 1996 (center; n = 58), and 2017 (bottom; n = 40).

Forest floor fuels (litter and duff) increased over time, driven by increases in duff which peaked in 2017 (Table 6). Surprisingly, litter and duff loadings just six years after the fire (in 1986) were comparable to those reported for unburned jack pine stands in the same study area (Simard et al. 1983). Although little duff was consumed in the Mack Lake

Table 6. Mean fuel loadings of organic layers, coarse and fine woody debris, and groundcover. Values presented are for 27 plots measured in 1986, 1996, and 2017. One standard error is shown in parenthesis. *Indicates significance at α = 0.05; pairs sharing a letter are not significantly different.

		1986	1996	2017
Organic Layers	Total (Mg/ha)	28.4 (2.2)	33.0 (1.5)	40.0 (1.7)
	Litter (Mg/ha)	12.8 (1.1)	13.5 (0.8)	12.3 (1.0)
	Duff (Mg/ha)*	15.6 (1.5)	19.4 (1.0)	27.2 (1.4)
Coarse Woody Debris	Total Biomass (Mg/ha)*	13.2^{a} (2.5)	3.7^{b} (0.7)	6.4^{ab} (1.2)
	Sound Biomass (Mg/ha)*	11.12^{a} (2.1)	3^{b} (0.6)	3^{b} (0.6)
	Rotten Biomass (Mg/ha)*	2.1^{ab} (0.4)	1.5^{a} (0.1)	4.3^{b} (0.6)
Fine Woody Debris	Biomass 1 and 10-hr fuels (g/m^2)	7.5 (0.8)	8.4 (0.7)	6.6 (0.5)
	Biomass 100-hr fuels (Mg/ha)	10.1 (1.3)	11 (1.1)	9.4 (1.1)
Groundcover	Height live woody (cm)*	51 (5)	86 (11)	57 (7)
	Height dead woody (cm)*	44 (3)	43 (4)	30 (4)
	Height live herb (cm)*	50 (4)	54 (3)	46 (2)
	Height dead herb (cm)	39 (2)	45 (3)	40 (3)
	Coverage live woody (%)*	56 (4)	56 (5)	37 (2)
	Coverage dead woody (%)	6 (1)	7 (1)	7 (1)
	Coverage live herb (%)*	51 (4)	47 (4)	37 (4)
	Coverage dead herb (%)	6 (1)	6 (0.7)	8 (1)
	Coverage moss (%)*	1 (0.3)	5 (1)	34 (5)

Fire, litter was significantly reduced (Simard et al. 1983), as is expected for fires in this system (Spaulding and Rothstein 2009). Caution should be exercised in interpreting estimations made on a small sample size (Simard et al. 1983), as post-fire litter depth has been reported to be highly spatially variable (Greene et al. 2007), becoming less spatially variable with post-fire stand age (Spaulding and Rothstein 2009). Estimates for litter and duff for this project were within the range of those reported by other studies (Spaulding and Rothstein 2009, Simard et al. 1983, Brown 1966), which happens to be very wide among different jack pine ecosystems and even across the same region. Fuels in general have been characterized by Keane et al. (2012) as being highly spatially variable and non-normally distributed, so that univariate analyses may not adequately explain patterns of landscape variability.

Several fuel classes peaked in mid-succession, particularly the height of live woody vegetation, which was greatest in 1996 (Table 6). Other important fuels such as dead woody vegetation height and live herbaceous height, and the coverage of live woody and herbaceous vegetation, were highest in the open conditions present in the decade after the fire (1986) but remained stable until 1996 (Table 6). These fuels are important “ladder fuels” that serve to transfer a fire from the ground to the canopy, potentially allowing the severity of a fire to increase from a surface fire to a crown fire and quickly increasing fire intensity (Van Wagner 1977, Atkins and Lundberg 2002). Van Wagner (1977) demonstrated how a fully stocked stand with a higher height to crown base was unable to carry a crown fire, whereas a surface fire was able to spread to the crown in a less dense stand with a shorter height to crown base. Together with the fact that canopy coverage of jack pine peaked in 1996 (Figure 4), the highest occurrence of ladder fuels in 1996 suggests that the potential for crown fire was highest in 1996 and has since decreased, although such fires are likely to be driven more by weather conditions than by fuels (Stocks 1989, Bessie and Johnson 1995). At the same time, the accumulation of duff has increased since 1986, and coarse woody debris has increased since its low in 1996 (Table 6). Duff and coarse woody debris are important fuel components of smoldering ground fires and subsequent surface fires (Lutes et al. 2006, Pyne et al.1996), suggesting that the flammability of forests at Mack Lake has not necessarily decreased over time. Overall, field data from this project suggest that the jack pine ecosystems at Mack Lake could be characterized as maintaining a constant surface flammability through succession, with the greatest danger of carrying a crown fire occurring in mid-succession. Thirty-seven years post-disturbance, the deep duff and increasing CWD biomass pose a greater risk for smoldering and/or a surface fire to occur. Notably, these data do not account for the likelihood of ignition at various points in succession.

Modeled changes in fuels vs. field data

Overall FVS did not represent fuels well over time and decreased in accuracy as the time since parameterization increased (Table 7). FVS parameterized using 1986/87 data accurately predicted fuels in all classes in the simulation for 1988, except litter was significantly higher in the field data than was predicted by the model (Table 7, Figure 6, $H(1) = 9.074$, $p = 0.003$).

Compared to 1997 field data, the model that was initialized using 1986 conditions was significantly different ($H(2) = 22.044$, $p < 0.001$); fuels < 3” and duff were both significantly lower in the modeled data ($p < 0.01$). The FVS simulation initialized using 1986 data was also significantly different than the field-based measurements from 2017 ($H(2) = 13.211$, $p = 0.001$). FVS underpredicted the amount of duff and fuels 3 – 6” ($p < 0.01$), and overpredicted the amount of fuels < 3” ($p < 0.01$).

Stand density was significantly lower over time ($F(1.039) = 7.108$, $p = 0.012$) and was different between measurement methods (Figure 7, $F(1.083) = 5.886$, $p = 0.020$). While density showed a trend toward self-thinning in the FVS-simulated stands, the initial density was overall significantly higher than field-based data, which was demonstrated by the interaction term, the measurement method at each time period ($F(1.106) = 9.594$, $p = 0.003$). Therefore, over the time period simulated, FVS did not accurately represent the stand dynamics of our system.

Table 7. Mean tons per acre of fuels in four fuels classes for FVS-modeled and field-collected data. Values in parentheses represent standard error of the mean. Asterisk indicates significant differences from the measured field data at $p < 0.01$.

	Model based on 1986 data			Model based on 1996 data			Field data		
Fuel Class	**1988**	**1997**	**2017**	**1988**	**1997**	**2017**	**1986**	**1996**	**2017**
< 3”	4.00 (0.49)	2.49 * (0.31)	9.16 * (0.88)	-	5.31 (0.49)	17.76 * (1.82)	4.34 (0.60)	4.73 (0.58)	4.23 (0.46)
3 – 6”	5.38 (0.61)	2.79 (0.32)	1.28 * (0.24)	-	2.47 (0.28)	2.37 (0.24)	5.68 (0.69)	1.95 (0.23)	3.27 (0.47)
Litter	4.04 * (0.33)	3.70 * (0.68)	4.06 (0.16)	-	5.71 (0.32)	6.98 * (0.50)	5.84 (0.47)	5.47 (0.37)	5.06 (0.41)
Duff	7.11 (0.68)	7.30 (0.67)	7.94 * (0.66)	-	8.94 (0.50)	10.07 (0.53)	7.05 (0.68)	9.10 (0.65)	11.47 (0.63)

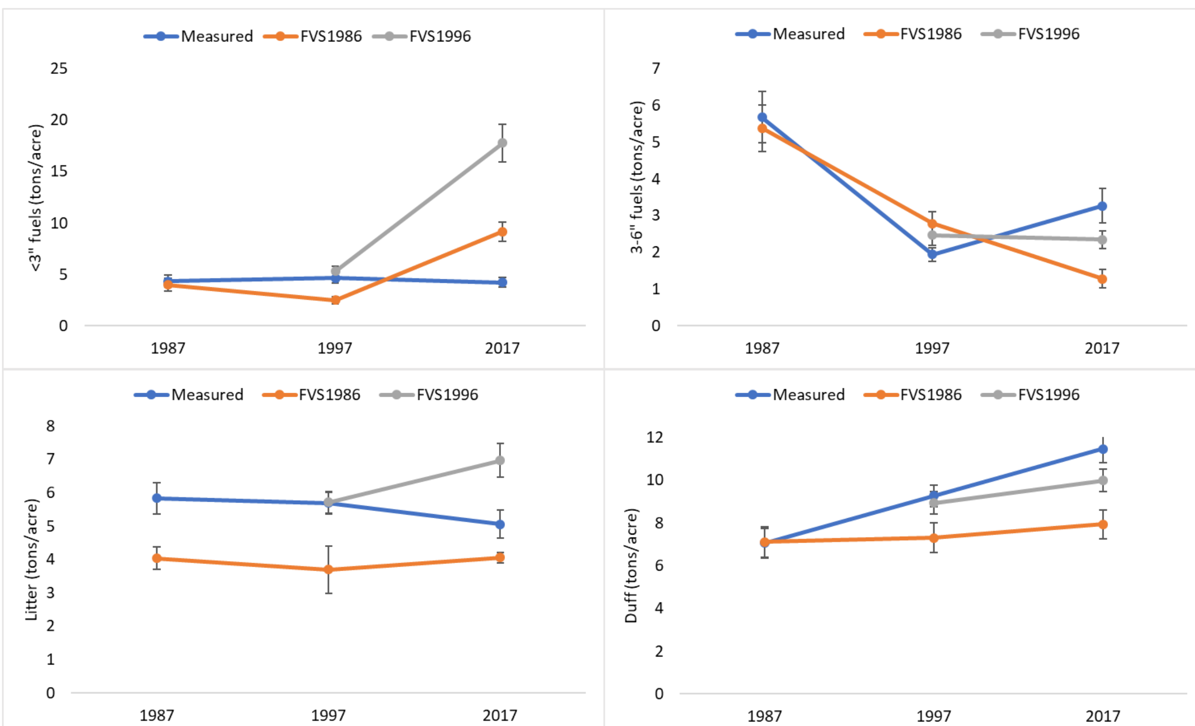


Figure 6. Means in tons per acre of fuels in four classes: < 3 in., 3-6 in., litter, and duff. Measured values represent field-measured data, FVS1986 are data generated from FVS runs initialized with 1986 field data, and FVS1996 are data generated from FVS runs initialized with 1996 field data. Error bars represent standard error.

Succession effects on fire behavior

Overall, Behave simulations with moderate fire weather scenarios displayed a decreasing trend of crown fires over time (Figure 8), with the likelihood of crowning as low as 10.5% in the oldest

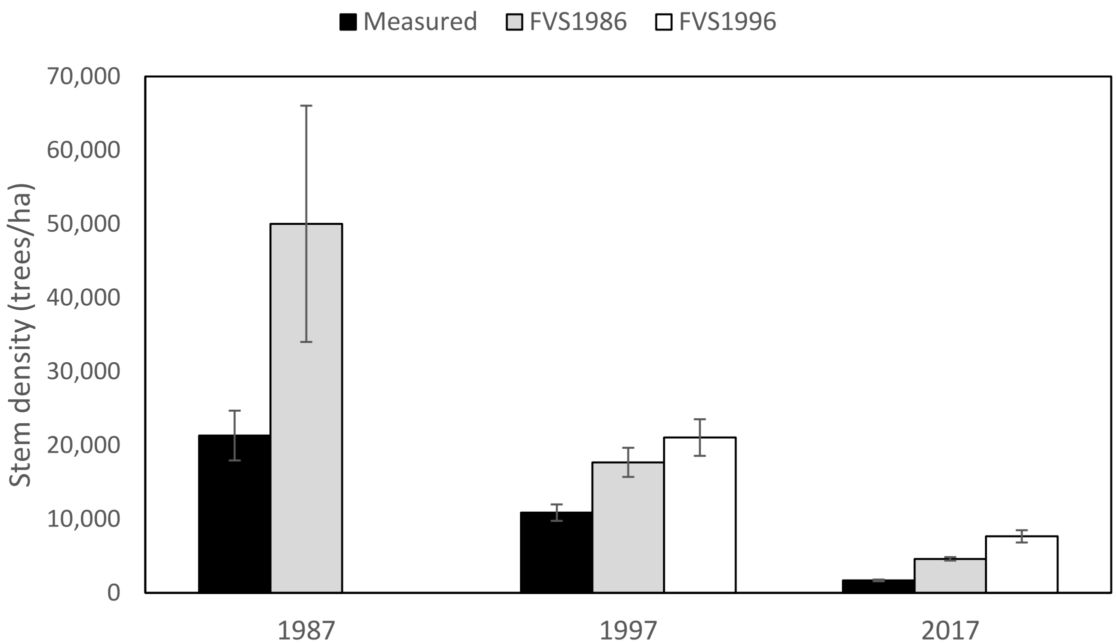


Figure 7. Average stand density (in trees/hectare) of field-measured stands, stands simulated by FVS initialized with 1986 data, and stands initialized using 1996 data. Error bars represent standard error.

stands. Under the severe fire weather scenarios the reduction was not as stark, but still reduced by nearly half in the oldest stands. This however does not necessarily correspond with observed fire behavior. For instance many of the fuels in the 1980 Mack Lake fire were between 35 and 70 years old (Simard et al. 1983), however the weather was even more extreme than our severe

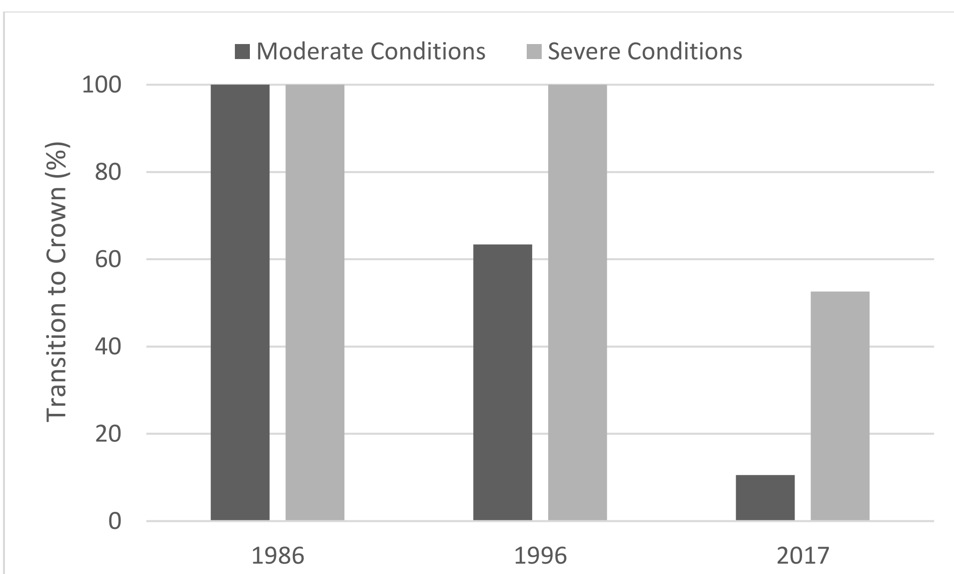


Figure 8. Percent of simulations that could produce enough energy to transition from a surface fire to a crown fire by year and fire weather scenario.

scenario here.

Both time and fire weather were significant factors, as was the interaction between them in all of the parameters reported. The surface rate of spread (ROS) was significantly higher in all severe weather scenarios compared to the moderate weather scenarios ($F_{(1)} = 690.626$, $p < 0.001$), and was overall highest in the youngest stands (1986, $F_{(1.148)} = 52.037$, $p < 0.001$). The critical surface intensity was highest in all moderate weather scenarios ($F_{(1)} = 390.63$, $p < 0.001$) and increased significantly over time ($F_{(1.247)} = 163.394$, $p < 0.001$). Transition ratio was highest in the youngest stands ($F_{(1.07)} = 82.596$, $p < 0.001$) and in the severe fire weather scenarios ($F_{(1)} = 96.147$, $p < 0.001$; Table 8).

The surface ROS peaked in the youngest stands, suggesting that larger amounts of surface fuels (Table 7) and young vegetation can best carry fire. The reduction in surface ROS in the 1996 simulations would correspond with typical canopy closure and reductions in moderate fuels documented during the time period. The transition ratio suggests that the youngest stands generate sufficient intensity to form a crown fire, but the likelihood decreases significantly over time (Table 8). This measure is likely inflated in the youngest stands by the low canopy of the young trees, and is reduced in the oldest stands by a higher canopy and canopy breakup that corresponds with typical stand development in jack pines.

Table 8. Results of Behave Plus simulations. Surface rate of spread (ROS) is the speed at which fire moves through surface fuels, and critical surface intensity is the intensity required to transition from a surface fire to a crown fire. A transition ratio < 1 has enough energy to transition to a crown fire.

	1986		**1996**		**2017**	
	Moderate	**Severe**	**Moderate**	**Severe**	**Moderate**	**Severe**
Surface ROS (m/min)	10.5 (0.4)	17.4 (0.7)	3.1 (0.1)	4.7 (0.2)	5.7 (0.7)	9.2 (1.3)
Critical Surface Intensity (kW/m)	13.8 (1.0)	11.5 (0.9)	213.4 (31.6)	177.6 (26.3)	995.5 (61.4)	829.1 (51.1)
Transition Ratio	84.9 (9.1)	194.5 (20.8)	4.1 (2.1)	8.9 (4.5)	0.6 (0.1)	1.3 (0.2)

Science delivery

Over the course of the project I have worked to communicate the process and findings of the study in several venues. The project served to train two individuals; a Masters student, who conducted the field work and examined successional changes in vegetation and fuels, and a postdoctoral associate, who conducted the FVS modeling to examine changes in fuels and fire behavior potential based on the field data. The Masters student presented her work as a poster presentation at three conferences; the 2019 Stewardship Network Conference in Lansing, MI in January 2019; the 2019 US Chapter of the Association for Landscape Ecology in Fort Collins, CO in April 2019; and the North American Forest Ecology Workshop in Flagstaff, AZ in June 2019. She completed her MS thesis and degree in July 2019 at Wayne State University. She plans to publish her thesis in a peer-reviewed journal within the next four months. The postdoc completed the modeling in August 2019 and presented her preliminary work as a poster presentation at the North American Forest Ecology Workshop in Flagstaff, AZ in June 2019.

Her work will be published in a peer-reviewed journal by June 2020. Results from both personnel will be summarized in a webinar and a research summary for the Lake States Fire Science Consortium (LSFSC). Finally, data developed from this project will be integrated in relevant classes at both undergraduate and graduate levels at Wayne State University (e.g., BIO 4130 General Ecology, BIO 5440/7440 Terrestrial Ecology, BIO 5540/7540 Landscape Ecology). In particular, the Terrestrial Ecology class will make field visits to the sample plots one weekend in September each year the course is offered; this began first in 2018.

Conclusions

Key findings

The objectives of this study – to assess changes in stand structure, plant community composition, and fuels over 37 years of succession and how those changes might affect future fire behavior – were met. Jack pine remained dominant at Mack Lake over the course of succession, though northern pin oak has increased in density. With overstory mortality already occurring and lack of regeneration, jack pine is likely to succeed to northern pin oak without fire. Many ecological species groups lost their ability to distinguish among landform-level ecosystems over time, probably because their coverage was reduced by increasing canopy closure that occurred with stand development. Fuels also changed over the 37-year sample period encompassed by this project. In particular, 1000-hr fuels were initially high after the fire, decreased to allow in 1996 then increased again by 2017 – consistent with other studies. Duff depth increased over time, as expected. Ladder fuels seemed to peak in mid-succession, as did canopy coverage. FVS poorly modeled fuels in this system, underpredicting organic fuels and overpredicting fine fuels, and also poorly represented stand dynamics in this system. Field data suggest that the jack pine ecosystems at Mack Lake could maintain a constant surface flammability through succession, with the greatest danger of carrying a crown fire occurring in mid-succession. Model results somewhat support these data, predicting that the likelihood of crown fires is highest in youngest stand and decreases with stand age – a trend very different than many crown fire-dominated coniferous ecosystems of the western US.

Implications for management

Overall, the major implication of this project for management is that fire management and decisions associated with it should occur in a dynamic sense, without assumptions that current conditions will be present after ten or even five years of succession or stand development. Acknowledging that managers always assess current conditions when managing for fire, the quantitative data from this project describing how vegetation and fuels change over time to influence flammability in this system is an essential decision-making aid for managers. Fuels data in particular suggest a constant potential for surface fires through succession in this system, but a higher potential for crown fires in mid-succession – a pattern that may affect management efforts on fire prevention and suppression efforts over time. Ecological species groups are designed to allow local managers to characterize and distinguish between ecosystems dominated based on their indicator value of site quality. The inability of many of the groups to maintain their effectiveness at distinguishing among ecosystems even as stand structure changed with age is notable, though I speculate this is more of a result of the methodology of species group construction than it is the concept of ecological species groups itself. The changes in potential fire behavior with time – with the probability of crown fire decreasing in older stands rather than the more conventional opposite trend - are notable from this project, and further reiterate that large fires in temperate jack pine-dominated ecosystems are more strongly controlled by weather systems than by the fuels complex.

Future research

Several additional aspects of the work will be included in the forthcoming refereed publications. The efficacy of ecological species groups should be further examined, especially by examining their ability to differentiate ecosystems over time. Species groups have been developed for a variety of different ecosystems types, particularly in the eastern United States, but my work suggests that the groups may lose their effectiveness as succession proceeds. Future research should examine whether this trend holds true in forests dominated by shade-tolerant as well as shade-intolerant species, as well as whether species group construction may be improved using multiple seres along the same successional trajectory. The inability of FVS to accurately model fuels in jack pine systems in this project implies the need for further study of the model itself; such work might examine whether jack pine in this region is an outlier systems in terms of model predictions or whether the Lake States Variant of FVS might be improved.

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Deliverable Type	Description	Status
Refereed publication	Successional changes in the effectiveness of ecological species groups in jack pine dominated ecosystems of northern Lower Michigan (Sosin and Kashian)	In preparation, to be completed by June 2020
Refereed publication	Changes in fuels and fire behavior potential over 37 years of succession in jack pine forests of northern Lower Michigan (Tucker, Sosin, and Kashian)	In preparation, to be completed by June 2020
Conference presentation	Julia Sosin poster presentation at the Stewardship Network Conference, Lansing, MI	Completed January 2019
Conference presentation	Julia Sosin poster presentation at US Chapter of the Association for Landscape Ecology, Fort Collins, CO	Completed April 2019
Conference presentation	Julia Sosin poster presentation at the North American Forest Ecology Workshop in Flagstaff, AZ	Completed June 2019
Conference presentation	Madelyn Tucker poster presentation at the North American Forest Ecology Workshop in Flagstaff, AZ	Completed June 2019
Webinar	Lake State Fire Science Consortium Webinar Series	Planned for 2020
Research Brief	Lake State Fire Science Consortium Research Brief – Changes in fuels over succession	Planned for 2020
Presentations given to managers	Twice-yearly presentations given to Kirtland's Warbler Recovery Team (disbanded in 2016)	Completed 2015-2016
MS Thesis	Successional changes in plant ecological species groups and fuels on a jack pine-dominated landscape in northern Lower Michigan	Completed July 2019
JFSP Final Report	Assessing 30 years of changes in vegetation and fuels following wildfire in jack pine forests of northern Lower Michigan: Project ID 15-1-07-15	Completed January 2020

Appendix C: Metadata

Data used for this project includes many measurements made over a 37-year period including tree species, diameter, height, and age data; species coverage of vascular plants; and the amount and distribution of organic and fine and coarse woody fuels. These data were gathered by several investigators and are stored within spreadsheet formats. The data will be submitted to the US Forest Service Research Data Archive for storage. Metadata was generated using the Morpho data management package for ecologists (Higgins et al. 2002) and will be submitted with this report and to the US Forest Service Research Data Archive.